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BIOMECHANICAL AND PHYSIOLOGICAL CONSIDERATIONS REGARDING VARIABILITY OF PHYSICAL WORKLOAD

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Rest allowances, job rotation, and job enlargement are often used as measures to reduce health risks caused by high physical loading. We investigated if and under which conditions a decrease in mean load can indeed be expected to reduce fatigue and health risks on the basis of a review on mechanical and physiological responses to variable loading versus continuous loading. The literature suggests that increasing variability in task demands may reduce health risks provided that a reduction of the mean work load is achieved.

INTRODUCTION

The aim of this paper is to provide a starting point of a framework to guide our thinking about variability in physical workload. In ergonomics, rest allowances, job rotation, and job enlargement are often used as measures to decrease the mean physical work load subjects are experiencing over a certain time period, with the ultimate goal of reducing fatigue and health risks caused by high physical loading. The question therefore is if and under which conditions a decrease in mean load can indeed be expected to reduce fatigue and health risks. This question will be addressed on the basis of mechanical and physiological responses to variable loading versus continuous loading. The first part of the paper will deal with biomechanical considerations, the second with physiological considerations.

BIOMECHANICAL ASPECTS OF VARIABILITY

From a biomechanical perspective, measures that increase variability of physical work load can reduce health risks only if cumulative loading at least in part determines the probability of tissue damage. We will review the evidence for this assumption below.

Spinal motion segments show an increased probability of endplate fractures with increasing numbers of cycles of compressive loading (Liu et al. 1983, Hansson et al. 1987, Brinckmann et al. 1988). Static compressive loading has not been shown to lead to direct injury, but does cause stress concentrations in the intervertebral disc, which may eventually cause injury or provoke pain (Adams et al. 1996, Deursen et al. 2001). However, endplate stresses were actually found to become more evenly distributed with reductions in peak stresses after static loading (Dieën et al. 2001b). Cyclic torsional movements of spinal motion segments with amplitudes that were initially non-damaging have been shown to cause mechanical changes indicative of injury (Liu et al. 1985). Cyclic bending combined with compression can lead to anulus ruptures and a consequent disc prolapse (Adams and Hutton 1985, Green et al. 1993, McNally et al. 1993). Solomonow et al. (2003) showed in an in vivo feline model that cyclic or sustained stretching of spinal ligaments, as would occur when bending the trunk, causes damage and inflammatory responses. In addition, it caused prolonged dysfunctioning of the paraspinal musculature, which might lead to further injury and pain.

Cyclic loading of tendons causes complete ruptures after many cycles (Schechtman and Bader 1997), but long before that substantial damage was found, coinciding with a reduction in stiffness (Schechtman and Bader 2002). Likewise, *in vivo* repeated contraction resulted in a reduced tendon stiffness probably indicative of damage (Kubo et al. 2001). In a rat model, Archambault et al. (1997) found indications of damage to tendon surfaces after repetitive loading.

It can be concluded that there is ample evidence that cumulative loading indeed partly determines failure probabilities of different anatomical structures and tissues. In addition, there is epidemiological evidence to support the clinical relevance of these findings (Kelsey et al. 1984, Silverstein et al. 1986, Silverstein et al. 1987, Kumar 1990, Norman et al. 1998, Hoogendoorn et al. 2000).

The mechanisms through which cumulative loading contributes to tissue damage are still a matter of debate. It is often assumed that accumulation of micro-damage (fatigue failure) is the main factor (Brinckmann *et al.* 1988, Green *et al.* 1993, Schechtman and Bader 2002). Other authors focus on visco-elastic strains (Goldstein 1981, Goldstein et al. 1987, Dieën and Toussaint 1995, Solomonow *et al.* 2003) and yet others propose friction to be the main mechanism (Moore et al. 1991). Differentiation between these mechanisms is difficult, since models based on these mechanisms may fit the experimental data equally well (Dieën and Toussaint 1997). In addition, these mechanisms are not mutually exclusive. Nevertheless their implications may be very different, especially in view of the differences in recovery rates. For example, visco-elastic strain can be expected to recover fairly quickly, whereas fatigue failure may take days to recover. Consequently based on visco-elastic strain job rotation should occur at a high frequency (Dieën and Oude Vrielink 1994), whereas fatigue failure models suggest that job rotation should occur for instance between days.

For compressive loading of the spine both fatigue failure and visco-elastic strain models indicate that the probability of injury is more strongly determined by the load magnitude than by loading frequency or the total number of load cycles (Dieën and Toussaint 1997). Likewise, for tensile loading of tendons around the wrist we have shown that fatigue failure and strain based models show a dominant influence of force exerted with the hands on injury probability over temporal characteristics of the loading protocol. Modeling the friction between these tendons and the surrounding tissue after Moore et al. (1991) shows force exerted and wrist posture to be the most important factors (Dieën et al. 1998b). This suggests that in general intensity of physical workload needs to be at a safe level, before increasing variability will substantially add to preventing injury. Evidently spreading high-risk jobs over many people will not bring down injury statistics (Frazer et al. 1999) **.**

PHYSIOLOGICAL ASPECTS OF VARIABILITY

From a physiological perspective, variability of the activity of muscle fibers can reduce health risks if it affects the development of fatigue and tissue damage. Although the precise mechanism is unknown, prolonged isometric contractions of the muscle, also referred to as static contractions, are a well-known cause of soreness and pain during and directly after the task performed. The muscular pain is produced during contractions in which the muscle tension generated is high enough to occlude the blood flow in the active muscle (ischaemia). Because of this ischaemia, an oxygen deficit occurs and metabolic waste products cannot be removed and thus accumulate to the point of stimulating pain receptors in the muscles. The pain continues until either the intensity of the contraction is reduced or the contraction ceases altogether, and blood flow is restored (Fox and Mathews 1981). Some experiments show that not only during high intensity jobs but also during low intensity jobs obstructions of the blood flow can occur (Sjøgaard et al. 1986). Although acute soreness is an annoyance, it is not seen as an important determinant for prolonged complaints (Fox and Mathews 1981).

A more probable pathophysiological mechanism has been proposed in the so-called Cinderella hypothesis (Hägg 1991). The activation of muscle fibers is performed in order of increasing size of the motor unit, according to the ‘size principle’ (Henneman et al. 1965). Therefore, the ‘Cinderella fibers’ as part of the small motor units are always active during prolonged work.

Sustained activity can result in damage of muscle fibers. A study of Lexell et al. (1997) showed that continuous stimulation at 10 Hz of the tibialis anterior and extensor digitorum longus of rabbits during 24 hours caused substantial fiber degeneration. This firing rate corresponds with that of motor units in the trapezius muscle during a typing task on a computer keyboard (Westgaard and DeLuca 1999). After continuous stimulation significantly more damage was found than after stimulation at 10 Hz at intervals of 1 hour on and 1 hour off. Although the volume percentage of damaged fibers was associated with the frequency of stimulation, the damage is not linearly associated with the aggregated number of impulses. Continuous stimulation at 5 Hz yields the same number of impulses as 10 Hz with intervals of 1 hour on and 1 hour off. However, the percentage degenerated fibers was about twice as high in the first condition. These results therefore suggest that indeed allowing for pauses in muscle activity may serve a protective effect.

Several studies in humans offer support for the beneficial effects of rest breaks. However, Duchateau and Hainaut (1985) found mixed effects on muscle fatigue during high intensity intermittent contractions in humans, when comparing a 60 s contraction with sixty 1 s contractions, separated by 0.5 s, 1 s and 2 s pauses. The 0.5 s pauses appeared to have an adverse effect. On the other hand, the 1 and 2 s pauses slowed down fatigue development. Van Dieën et al. (1993) examined differences in the activity pattern of the trunk extensor muscles between groups of subjects with high and low endurance. The high endurance group was characterized by significantly more variability of the EMG amplitudes over successive contractions.

Veiersted et al. (1993) studied the relationship between muscle activity patterns and muscle pain in a standardized and machine-paced work task. Workers showing more frequent short (< 1 s) interruptions of muscle activity, coined EMG gaps, had a lower probability of developing muscle pain. The beneficial effect of EMG gaps may be surprising given the results of Duchateau and Hainaut described above. However, Westgaard and De Luca (1999) found that EMG gaps during a typing task were indications of alternating activity between motor units, allowing longer derecruitment of previously active motor units.

DISCUSSION

The literature reviewed suggests that increasing variability in task demands may reduce health risks provided that a reduction of the mean work load is achieved or periods allowing recovery are introduced. This can be done either through job rotation, rest allowances, or similar measures.

It is important to note that biomechanical and physiological effects of sustained loading will interact and in most cases this interaction will amplify the risk of injury. For example in repeated lifting, back muscle fatigue and flexion creep of the spinal ligaments will occur. Both factors may contribute to an increased trunk flexion over repeated lifts, which promotes further creep and causes increased spinal compression (Dieën et al. 1998a, Dieën et al. 2001a). This amplification of effects emphasizes that a substantial reduction of injury risks can be made by providing adequate possibilities for recovery.

Even in the absence of variability in the task demands, considerable variability in physical loading may occur. For example in repeated lifting, the within subject coefficient of variation of the peak spinal compression was around 10% (Dieën *et al.* 2001a). Mathiassen (2001) found during a very stereotypical experimental task (holding the arms 90 degrees abducted) within subject coefficients of variation in trapezius EMG amplitude with a median value of about 8% and a maximum across subjects of 25%. Also the EMG gaps described above can be considered an example of such spontaneous variability. As discussed above variability may have biomechanical and physiological benefits. From an ergonomics perspective it is important to realize that the scope for variability is determined by task constraints. Tasks requiring large effort or high precision will probably not allow much variability.

It is possible that a variable physical workload has a more far-reaching effect than merely reducing health risks. A well-balanced variable physical workload might actually promote health rather than just reducing health risks, because of its effects on the load bearing capacity of anatomical structures. First of all it is important to note that absence of physical loading has a negative effect on the load bearing capacity of anatomical structures as is well known from for instance findings after prolonged stay in space. Conversely it is well known that physical loading causes an increase in the load bearing capacity of the same structures (e.g. Granhed et al. 1987, Porter et al. 1989, Kubo et al. 2002). Recent work on osteoporosis (Homminga 2003) provides an interesting hypothesis on adaptation to physical loading. Numerical analysis predicted osteoporotic vertebrae to be equally strong as normal vertebrae under loads occurring frequently in daily life. However, the osteoporotic vertebrae were predicted to be much less resistant to loads occurring in an unusual direction. An odd movement could thus easily cause injury. One explanation for this finding could be that the limitations in movement behavior that often occur with ageing lead to adaptation to the limited set of loads encountered regularly. Thus to avoid injury it may be necessary that a wide range of physical loads is encountered at a regular basis. In addition, it is known that variability in loading is necessary to maintain tissue health because it promotes fluid exchange. This holds for the venous return from the legs which is improved by intermittent contraction of calf muscles (Winkel and Jorgensen 1986) and for avascular structures such as the intervertebral disc, which require variable compressional loads for fluid exchange and exchange of large nutrients (Holm et al. 1981).

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